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Absorption of Cosmic-Ray Particles Generating Electron-Nuclear Showers

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In the summer of 1951, we measured the absorption of particles generating electron-nuclear showers in graphite, iron, and lead. The work was done in Pamir at an altitude of 3860 m. Fig. 1 is a diagram of the apparatus. Each counter was connected with its light of the hodoscope which was triggered by the triple coincidences of counters *I*, *II*, and *III*. These coincidences selected the cases of formation by ionizing particles of a shower containing at least two penetrating particles. The thickness of lead between the adjoining counters *II* and *III* was at least 4 cm.

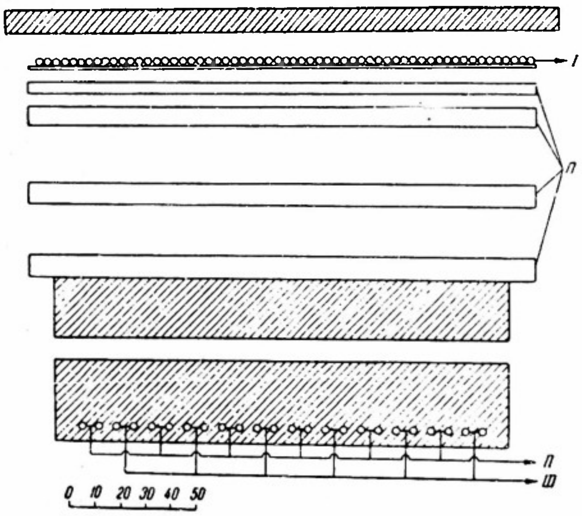

Fig. 1.

There was always a thickness of 56 cm of lead between the absorber *P* and the counters *II* and *III* in order to avoid the transition effect in the absorber.[1,2] (For example, it can be seen from the absorption curve of electron-nuclear showers in water[3] that the transition effect in an absorber becomes negligible at a depth of two or three mean free paths for the interaction with nuclei of the particles which generate electron-nuclear showers.) The iron or lead absorbers were arranged in layers in such a way as to make their volume equal to the volume of the graphite absorber.

In our work, we selected only those hodoscopic photographs that showed the registration either of two nonadjoining counters or of three or more counters of groups *II* and *III*. With this selection system, electron-nuclear showers generated by particles with an energy greater than 10^{10} ev were registered. Cases in which more than one counter of group *I* was triggered were excluded, i. e., only the events caused by a single penetrating ionizing particle crossing the apparatus were studied.

The basic results of the measurements are given in Table I. The fourth column gives the values of the mean free path for an absorption λ_p of the component generating electron-nuclear showers. The last column gives the ratio of λ_p to the mean free path λ_g, corresponding to the so-called

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" geometrical" cross section of the nucleus, $\sigma = \pi \times 1.4^2 A^{2/3} \times 10^{-26}\,\mathrm{cm}^2$; the value of λ_g is close to the value of the mean free path, λ_i, for the interaction of the particles generating the electron-nuclear showers.

Table I.

	No. of counters *II* and *III* which registered N_c	No. of events per hour*	λ_p in gm $\times$ cm^{-2}	λ_p/λ_g
Without absorber	2	3,39±0,13		
	3	3,80±0,13		
	≥4	1,57±0,09		
	≥3	5,37±0,16		
Graphite 152 gm $\times$ cm^{-2}	2	1,96±0,08	278±29	
	3	1,92±0,08	223±18	
	≥4	0,74±0,05	203±27	
	≥3	2,66±0,10	216±15	3,5
Iron 252 gm $\times$ cm^{-2}	2	1,82±0,10	405±42	
	3	1,91±0,10	366±23	
	≥4	0,67±0,06	295±35	
	≥3	2,58±0,11	344±25	3,4
Lead 365 gm $\times$ cm^{-2}	2	1,85±0,08	603±58	
	3	1,71±0,08	457±33	
	≥4	0,81±0,05	553±71	
	≥3	2,52±0,10	482±31	
	≥2	4,37±0,12	527±28	3,0
Lead 160 gm $\times$ cm^{-2}	≥2	6,30±0,22	496±64	

*Corrected for accidental coincidences

The following conclusions can be inferred from the table:

(1) The comparison of the absorption values when a varying number N_c of counters of groups *II* and *III* have registered shows the absence of the transition effect which should have reduced the measured value of absorption for greater N_c's (we observed this effect by using a similar apparatus, with, however, a smaller thickness of the absorber and of the permanent lead layers under the absorber.)

The equality (within the limits of error of measurement) of the values of λ_p measured for two different thicknesses of lead also indicates the absence of the transition effect.

A certain reduction of absorption for the smallest N_c's is apparently caused by the registration of a small number of showers produced by electromagnetic interaction of high-energy μ-mesons.

(2) The measured value λ_p is substantially greater for graphite than the corresponding value for air ($\sim$120 gm/cm^2); see reference 1. In the absence of the influence of the transition effect, this fact means that the component generating the electron-nuclear showers contains particles which decay. The proportion of these particles can be estimated from the relation

$$\lambda_i = \lambda_p (1 - \bar{s}), \tag{1}$$

where $\bar{s}$ is the average effective number of nuclear-interacting particles formed by a single interaction between the incident particle and the atomic nuclei of the matter.

Eq. (1) applies not only to the particular hypotheses on the basis of which this equation was derived in references 2 and 4, but also to a quite general case, as can be shown from the kinetic equations for appropriately averaged values of λ_i and s. (In reference 3, in order to estimate the

proportion of decaying incident particles by comparing the absorption in water and in air, the incorrect relation $\lambda_{air} = \lambda_{water}(1 - \bar{s})$ was used.)

Since the value λ_i for air and graphite is ~60 to 70 gm/cm^2, we would find from (1) that in air $\bar{s}$ is 1/3 as large as in graphite. Thus, about 1/3 of the particles generating electron-nuclear showers in a dense substance have time to decay completely in air at average altitudes.

If it is assumed that these decaying particles are principally π-mesons, then, insofar as, in the case of the energies of ~10^{10} ev selected by the apparatus, the mean free path for decay may be compared with the path for interaction in air, even in air π-mesons must constitute an appreciable fraction of the particles that generate the electron-nuclear showers; in a dense substance, their proportion must be well over 1/3.

(3) In lead, absorption is substantially smaller than in a graphite layer of equal mass. The absorption in layers of graphite, iron, and lead of equivalent λ_i values is equal, and therefore the absorption during the passage through the nucleus is also equal to a first approximation.

(4) The value of λ_p for all three substances is approximately three times as great as λ_i, i.e., $(\lambda_p/\lambda_i)_C \approx (\lambda_p/\lambda_i)_{Fe} \approx (\lambda_p/\lambda_i)_{Pb} \approx 3$. This means that the absorption of nuclear-interacting particles, together with the secondary nuclear-interacting particles produced by them, takes place on the average after about three interactions with the nuclei.

However, the cross section for the interaction with the nuclei of the incident particles is similar in magnitude to the geometrical dimensions of the nucleus. Hence, when these particles pass through heavy nuclei, successive collisions with nucleons inside the same nucleus must take place. Nevertheless, the loss of nuclear-interacting particles during the passage through one nucleus is about the same for light and heavy substances despite the different number of collisions with nucleons inside the light and the heavy nuclei.

There are two possible explanations for this peculiarity. The first is that, for energies of the order 10^{10} ev, the fast incident particle interacts with the nucleus as a whole, and the results of the interaction do not depend much on the atomic number of the nucleus. The second explanation, based on the assumption that when nuclear-interacting particles pass through a nucleus, they can consistently interact with various nucleons or groups of nucleons, is as follows: The π^0-mesons, appearing during the formation of the electron-nuclear shower, decay as they leave the nuclei in which they were formed, producing photons, and, from the viewpoint of the nuclear cascade process, the energy transmitted to them can be considered irreversibly lost. In heavy nuclei, an internuclear cascade process must occur with the participation also of π^0-mesons, as a result of which the energy transferred to the latter will to some extent become a part of the energy of the nuclear cascade and correspondingly reduce its attenuation. Thus, the reduction of the number of nuclear-interacting particles must be less after passing through one heavy nucleus than after passing through several light nuclei with the same number of nucleons in the path of the nuclear-interacting particles.

Besides the π^0-mesons, a similar effect may be caused by other nuclear-interacting particles decaying with a mean free path that is small or comparable with the path [necessary] for interaction in a dense substance, and producing particles which do not interact with nuclei. Our quantitative estimate of this effect, based on Eq. (1), shows that such an explanation

is possible for our experimental data.

Insofar as inside heavy nuclei π^0-mesons lose part of their energy in nuclear interactions, it must be expected that the energy transmitted to the electron-photon component will be smaller in heavy substances than in light substances of equal mass.

The internuclear cascade process must result in the partial loss in energy of the nuclear-interacting particles which have interacted. Therefore, the average energy of nuclear-interacting particles leaving heavy nuclei must be somewhat smaller than that of the particles leaving light nuclei. Since the absorption in light and heavy substances nevertheless occurs after an equal number of interactions, it follows that, on the average, a greater number of nuclear-interacting particles issues from the heavy nuclei.

In examining the possible mechanisms of the internuclear cascade process, we cannot disregard the possible case of several nuclear-interacting particles (produced in the same nucleus and leaving at a small angle) interacting with the same nucleon.

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